(10) by
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(6) TRENDS IN MISSILE AND SPACE RADIO TELEMETRY (7)-(9) NA

1. EARLY HISTORY (11) [1962] (12) 45p (13) NA

The humble beginnings of the radio-telemetry art go back to the 1930 period, when successful flights of weather beacons were made in Germany. Temperature and humidity data were transmitted at that time as a function of pressure. The frequency of a transmitting oscillator was in turn controlled by the temperature and humidity sensor outputs via a commutator activated by a pressure-sensitive bellows.

A requirement for multi-channel radio telemetry with much larger data capacity emerged during World War II in conjunction with the testing of experimental military aircraft. It was desired to obtain as much performance data as possible without the risk of losing the data in case of a crash. Even more obvious was the need for good radio-telemetry equipment in the case of the automatic weapons developed at Peenemuende. In spite of considerable effort put into the development of suitable multi-channel systems, not much useful information was gained through radio telemetering during the years of the war. MESSINA I, an amplitude modulation multiplex system used often during the extensive flight test phase of the V-2, proved rather inadequate. It is well known today that amplitude modulation is quite unsuitable outside the laboratory because noise tends to degrade the information easily. With the transmission going directly through the attenuating exhaust flame, insufficient signal-to-noise ratios were obtained, and rarely was it possible to recognize significant data trends because of the overwhelming noise. The subsequent development of a frequency-modulated system (MESSINA II) led to flyable equipment (called "Kindersarg" because of its size) during the closing days of

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Peenemuende, but mostly too late to aid in the critical stages of flight testing. I still remember vividly the many post-mortem conferences in which Dr. v. Braun and his key group of scientific personnel sat together trying to figure out what could possibly have been the cause of failure during the previous mission. More often than not the diagnosis was based on evidence such as, "Through my binoculars, I saw that the rudder was locked at the extreme position," or on the largely uninformative trajectory data obtained by cinetheodolites or the Doppler system.

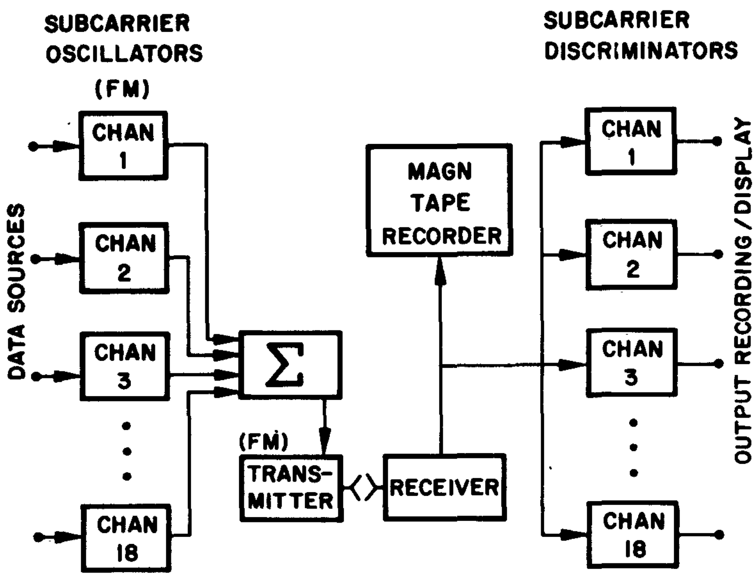
At that time, relatively little was recorded concerning the theoretical performance characteristics of various modulation schemes. After the war's end, this situation persisted for some years in the United States, where a variety of modulation schemes were tried, while little effort was devoted to arriving at scientifically optimum devices. From the efforts of a number of independent agencies, however, emerged a nucleus of practical and useful contemporary systems. The first was the pulse-position modulation system (PPM-AM) of the Naval Research Laboratory. This was a system in which the time separation between a reference pulse and an information pulse was proportional to the measured value of each channel; thus a sequence of pulses of constant amplitude was transmitted, half of them occurring at regular intervals and half of them at irregular times in between, commensurate with the various measurement values. There were twenty-three time-multiplexed channels. The pulses were short and of relatively high peak power (2kw); the bandwidth was in the megacycle range, with the carrier frequency at approximately 1,000 Mc. Multiplexing was performed by gas-filled vacuum tubes acting as switches. This system functioned well for a number of years, until about 1950, in conjunction with the Navy's Viking (the first American-designed rocket), the German V-2's fired at White Sands, and the Hermes II, the first missile project pursued by Dr. v. Braun in the United States.

For moderate data requirements such as encountered with small air-to-air missiles, pulse duration modulation (PDM) systems proved appropriate. In a typical PDM/FM system, a mechanical commutator is used to sample a limited number (approx. 30) of channels at a relatively low rate (approx. 30/sec). The resulting amplitude-modulated pulses are converted to pulses of variable duration, the duration being proportional to the measurement value to be transmitted. The resulting pulse-train voltage is used to frequency-modulate a VHF carrier. PDM systems are more easily implemented for low-power, low-data-rate applications, and they do not require the uncomfortably high transmitter voltages associated with the short, high peak-power pulses of PPM-AM.

It was the FM-FM concept, however, which ultimately acquired prominence and appeared to be the most appropriate in the light of increasing needs for higher data rates in most flight testing programs. Multiple subcarriers are provided with relatively wide data bandwidth associated with the higher frequency subcarriers. Reactive sensors can directly modulate the subcarrier oscillators (otherwise voltage-controlled oscillators are used) and, with adequate subcarrier frequency deviation, a high degree of immunity to noise is achievable. Since VHF telemetering band limitations became obvious not long after this type of equipment was used by a number of projects at the ranges, strict adherence to narrow frequency tolerances became necessary. Crystal-stabilized transmitters are now universal.

2. STANDARDIZATION

The standardization committee of the Inter-Range Instrumentation Group (IRIG) of the United States Missile Ranges decided to standardize the FM-FM telemeter as the most practical large-capacity system available at the time. Accordingly, specifications were issued in 1948 and revised 1954. Reference is made to Fig. 1. The frequency response of the various subcarriers should ideally match the information content of the measurement quantities to be transmitted in order to utilize system capacity as fully as possible. However, in practical cases this can be achieved only to a lesser extent. The two highest subcarrier channels are frequently subcommutated to accommodate the usual multitude of low-frequency data channels. For the time-multiplexed subchannels, the mode of modulation is PAM-FM-FM. Generally, 30 or 60 channels are sampled at a rate commensurate with the bandwidth of the high-frequency subcarrier, this rate being up to 30 times/sec. The individual channel information bandwidth is thus limited to approximately 10 cps or less. Commutation is still widely done with mechanical commutators.



CHANNEL	CENTER FREQUENCY CPS	DEVIATION LIMITS[1] CPS	FREQUENCY RESPONSE[2] CPS
1	400	370 / 430	6
2	560	518 / 602	8.4
3	730	675 / 785	11
4	960	888 / 1,032	14
5	1,300	1,202 / 1,398	20
6	1,700	1,572 / 1,828	25
7	2,300	2,127 / 2,473	35
8	3,000	2,775 / 3,225	45
9	3,900	3,607 / 4,193	59
10	5,400	4,995 / 5,805	81
11	7,350	6,799 / 7,901	110
12	10,500	9,712 / 11288	160
13	14,500	13,412 / 15,588	220
14	22,000	20,350 / 23,650	330
15	30,000	27,750 / 32,250	450
16	40,000	37,000 / 43,000	600
17	52,500	48,562 / 56,438	790
18	70,000	64,750 / 75,250	1,050
A THROUGH E[3]	22,000–70,000	±15%	660–2,100

(1) MAXIMUM SUBCARRIER DEVIATION CHANNEL 1-18: ±7.5%
(2) FREQUENCY RESPONSE BASED ON DEVIATION RATIO OF 5
(3) OPTIONAL CHANNELS; IF USED OMISSION OF ADJACENT CHANNELS NECESSARY

Fig. 1 FM-FM Telemetry System

Standards were also issued at the same time for PDM-FM telemeters. These standards, which specify from 300 to 1,500 samples/sec total, provide the basis for small, lightweight, low-power equipment.

Standardization froze out some promising system developments current at the time and, thus, did . certain amount of long-range harm. On the other hand it aided the immediate situation immeasurably by eliminating the many different types of ground equipment which threatened to overflow the blockhouses of the test ranges. Subsequently, many millions of dollars worth of standardized ground equipment was installed at all test range sites, and through the years since, the bulk of telemetering data in the missile and space field in the United States has been obtained by means of the FM-FM system. The performance in literally thousands of missions has been gratifying as to accuracy and reliability.

3. SYSTEM COMPARISON

About the time the IRIG issued its standards, serious investigators were engaged in analyzing various modulation schemes for their relative merit; the book Radio Telemetry by Myron H. Nichols and Lawrence L. Rauch, originally published in 1954, is the first significant sign of the systematic scientific approach to telemetering. As shown by Nichols and Rauch and others, all modulation schemes which spread out the information over a bandwidth substantially wider than the information bandwidth lead to significant improvement of the output signal-to-noise ratio. The added predetection noise due to the additional bandwidth is less influential than the better definition of the message possible because of the wider bandwidth. The improvement applies to frequency modulation, where the improvement factor over amplitude modulation is $\sqrt{3 \cdot D}$, D being the ratio of the carrier frequency deviation to the highest modulation frequency. Figure 2 shows that the SNR for AM is identical in the IF and after demodulation. A remarkable improvement of output SNR occurs in FM for all cases involving increased IF bandwidth or, essentially, for deviation ratios larger than one. It can be observed that the improvement is dependent on the signal levels exceeding certain thresholds; at lower

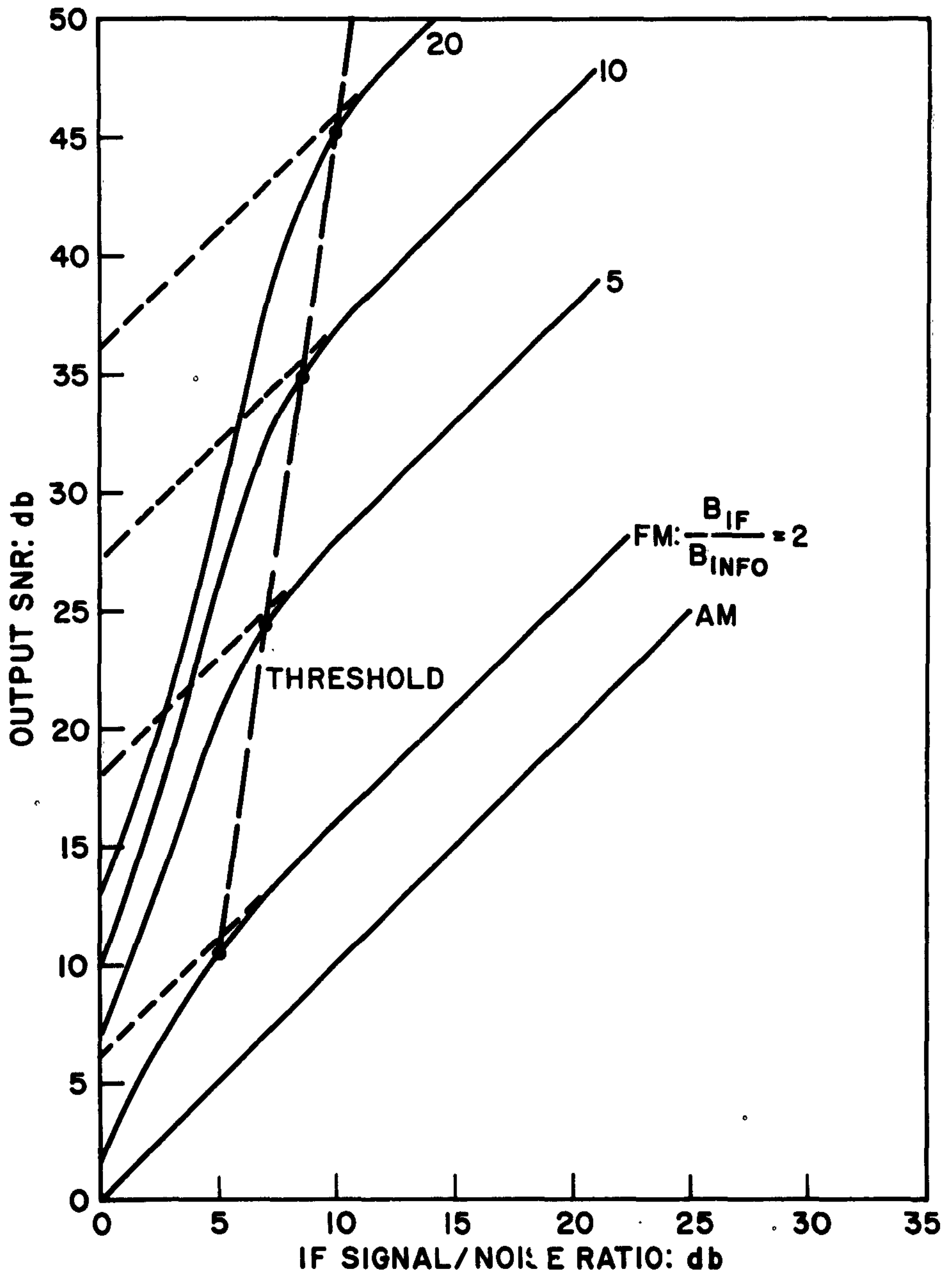


Fig. 2 AM and FM Signal/Noise Characteristics

absolute signal levels the improvement fades quickly, and at very low levels, FM becomes inferior to AM. It is important under all operating conditions to exceed the threshold continuously and to avoid the marginal condition.

While FM-FM shows the desirable characteristics of wideband improvement, it is not necessarily superior to other modulation schemes with regard to bandwidth utilization, accuracy, weight, size, and power consumption. If the results of more recent studies on relative efficiency of various modulation schemes had been known to the Standardization committee of the IRIG in 1950, it is likely that at least further research and development would have been recommended for time-division systems and also for some more exotic analog modulation schemes that are now under consideration. Early time-multiplex implementations such as the described PPM-AM system of NRL (1947) and the PAM-FM systems of Princeton (1946) and MIT (1951) were reasonably promising even though cumbersome and somewhat handicapped by the lack of solid state switching elements at that time. Subsequently, with advances in component technology, particularly switching diodes, the temporarily outcast schemes were to come back and strongly so.

In later years, not only did the number of missions increase but also the number of measurements per flight. To accommodate the data of a multistage rocket mission, it was no longer sufficient to fly one FM-FM telemeter, but two, three, or even four were needed. Operation and reliability problems became acute, and increasing congestion plagued the assignment of frequencies in the limited VHF telemetering band.

A typical complement of data for a large mission of, say, two years ago is shown in Table 1. If instrumentation schedules such as shown (modest by even more recent practice) are arranged to fit the format of the FM-FM system, the use of multiple links is mandatory. Rarely however do the information rates altogether fit the available channel rates sufficiently well to utilize the full inherent capacity of the FM-FM system. Often channels of modest frequency response requirements are assigned to intermediate subcarriers capable of handling higher information frequencies, and the high-frequency

Table 1 TYPICAL MULTI-ACCURACY AND MULTI-BANDWIDTH DATA

Item	No. of Data Channels	Range	% Accuracy	Channel BW	Total Information BW	Type of Data
1	4	0-5 V	10	2 kc	8000	Amplified output of vibration transducers
2	13	0-5 V	2-5	50 cps	650	Guidance & control function monitors
3	29	0-5 V	2	20 cps	580	Electronic equipment monitors
4	28	0-5 V	0.2	0.5 cps	14	Payload data
5	110	0-50 mv	2	2 cps	220	Thermocouple and strain gauge data
6	106	0-5 V	2.5	5 cps	530	General T/M data
Total	290				9.994 kc	

subcarriers are subcommodated, making them largely unavailable to the wideband demands of certain measurements, such as those originating from vibration transducers. Although the 10,000-cps requirement of Table 1 might theoretically be handled by 2-1/2 FM links, it is not likely that even four systems would suffice in practice to accommodate the listed data because of the inflexibility of FM-FM channel characteristics.

One of the companies faced with this dilemma was Lockheed Missiles & Space Company in its extensive telemetry programs for both the Polaris missile and various complex satellite missions. Therefore, enlarging on previous investigations, it made a more thorough theoretical and practical comparison between the performance of PAM-FM, FM-FM, and others. This study clearly showed the superiority of the former system, even under the unrealistic condition where the FM-FM system was credited with carrying the maximum possible information per subcarrier channel. These Lockheed investigations subsequently were fully confirmed and supplemented by a tri-service study performed by the Aeronutronic Division of Ford Motor Company (8). This organization had been requested to study practical solutions to the threatening multi-link situation arising in connection with large-scale flight tests. In Table 2, the relative performance of FM-FM, PDM-FM, and PCM-FM is analyzed with reference to PAM-FM. The total data capacity of an FM-FM link is approximately 4 kcps and, for comparison purposes, the time-multiplex systems on the right are tailored to the same data capacity. At the chosen level of 1 to 2 percent accuracy, PAM-FM turns out to be lowest in power per unit of information and also requires the lowest over-all bandwidth. All three time-division systems are superior to FM-FM.

Practically speaking, the situation is even less in favor of the largely inflexible subcarrier arrangement of the FM-FM system. Instrumentation schedules and the frequency statistics of channels vary considerably from test to test, depending on the scientific mission. Time-division multiplex systems, such as PAM-FM, are basically superior to the frequency multiplex system in that they are much more adaptable to specific instrumentation schedules, particularly to schedules which, as shown in Tables 1 and 3, require the handling of data differing widely in frequency requirement and

Table 2 COMPARISON OF FOUR MODULATION SCHEMES (REF. AERONUTRONIC REPORT U-743)

	IRIG FM-FM	PAM-FM	OPTIMIZED PDM-FM $\left(\begin{array}{l} d_{min} = 0.1/f_s \\ d_{max} = 0.75/f_s \end{array}\right)$	PCM-FM (BINARY)
B_{INFO}	4 kc (1)	4 kc	4 kc	4 kc
RMS ERROR (ALL SOURCES)	2%	1.6%	1.6%	1.08% (2, 3)
$f_{sampling}$	–	10 kc	10 kc	10 kc
f_{bit}	–	–	–	50 kc
DESIGN B_{IF}	300-500 kc	60 kc (4)	100 kc (4)	50 kc (4)
PEAK DEV.	125 kc (40 kc RMS)	22 kc	38 kc	25 kc
B_{VIDEO} (RCVR OUT.)	100 kc	10 kc	50 kc	25 kc
B_{PREMOD} (XMTR IN)	100 kc	30 kc	50 kc	25 kc
CARRIER-NOISE (B_{IF}) (5)	6-8 db	9.9 db	9.2 db	12.6 db (3)
CARRIER-NOISE (B_{INFO})	26.2 db	21.7 db	23.2 db	23.6 db
RELATIVE REQ'D POWER	2.82 +4.5 db	1.0 0 db	1.41 +1.5 db	1.55 +1.9 db
SPECTRUM BW -40 db (6)	300 kc	60 kc	155 kc	100 kc

(1) ONE FM-FM LINK

(2) RMS QUANTIZING ERROR = $2^{-5}/\sqrt{12}$ = 0.9%

(3) BIT ERROR PROBABILITY = $10^{-4} \rightarrow$ 0.6% EQUIVALENT RMS ERROR

(4) CUSTOMARILY EXPANDED SOMEWHAT TO ACCOMMODATE FREQ. UNCERTAINTY

(5) APPROXIMATE THRESHOLD

(6) -40 db RELATIVE TO UNMODULATED CARRIER

Table 3 CHANNEL-BANDWIDTH STATISTICS FOR SATELLITE MISSION

INFORMATION BANDWIDTH	NUMBER OF CHANNELS	CUMULATIVE TOTAL OF CHANNELS	TOTAL INFORMATION BANDWIDTH PER TYPE CPS	CUMULATIVE TOTAL OF INFORMATION BANDWIDTH	CUMULATIVE TOTAL OF INFORMATION BANDWIDTH
cps	—	%	cps	%	cps
0.1	14	2.6	1	6.2×10^{-3}	1
0.2	50	12.0	10	6.8×10^{-2}	11
0.5	80	26.9	40	3.1×10^{-1}	51
1	110	47.5	110	1.0	161
2	109	67.8	218	2.5	379
5	51	77.4	255	3.9	634
10	56	87.8	560	7.4	1,194
20	39	95.2	780	11.1	1,974
50	3	95.6	150	13.2	2,124
100	11	97.6	1,100	20.0	3,224
200	2	98.2	400	22.5	3,624
500	3	98.8	1,500	31.8	5,124
1000	3	99.3	3,000	50.5	8,124
2000	4	100.0	8,000	100.0	16,124
TOTALS	535		16,124		

number of channels of a specific class. In the typical case of a data complement such as shown in Table 1, one PAM-FM system suffices to carry the information which four FM-FM systems might be hard pressed to handle. Figure 3 has been drawn to illustrate the practical comparison based on a very similar data requirement.

4. DEVELOPMENT OF LOCKHEED PAM/FM SYSTEM

A research and development program was therefore initiated and a PAM-FM system produced which by now has demonstrated its broad capabilities and high reliability in a large number of successful missile and satellite flights.

Figure 4 shows a high-rate system in which multiple channels are sampled sequentially. Typically, there are 40,000 samples/sec and 16 samples per basic frame. The 16 pulses within one frame correspond to the 16 main subchannels of the system. Each of the 16 subchannels is sampled at the frame rate, i.e., 2,500 times/sec, resulting in a basic channel bandwidth of approximately 1,000 cps.* Channel 1 alternates between synchronization (total absence of pulse) and maximum data calibration, Channel 11 between zero data calibration and synchronization. A pedestal is used beneath the information voltage to obtain better recognition of the sample frequency under noisy conditions.

The process of sampling is fundamental to the pulse-amplitude modulation format and will be discussed briefly. It can be proven mathematically that information in a signal of bandwidth W is fully described by instantaneous amplitude samples taken at the rate $F = 2W$. This corresponds to 2 samples taken per highest frequency present. If sampling is achieved at this rate, all information can theoretically be recovered by applying the proper interpolation process. This, naturally, presupposes noise-free transmission. The ideal interpolation function is of the sin x/x variety, x being determined by sampling rate F, as shown in Fig. 5. Interpolation can be performed in a digital computer or by analog devices such as tapped delay lines or other low-pass

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*Only subcarrier channel 18 of the FM-FM system has equal bandwidth capability.

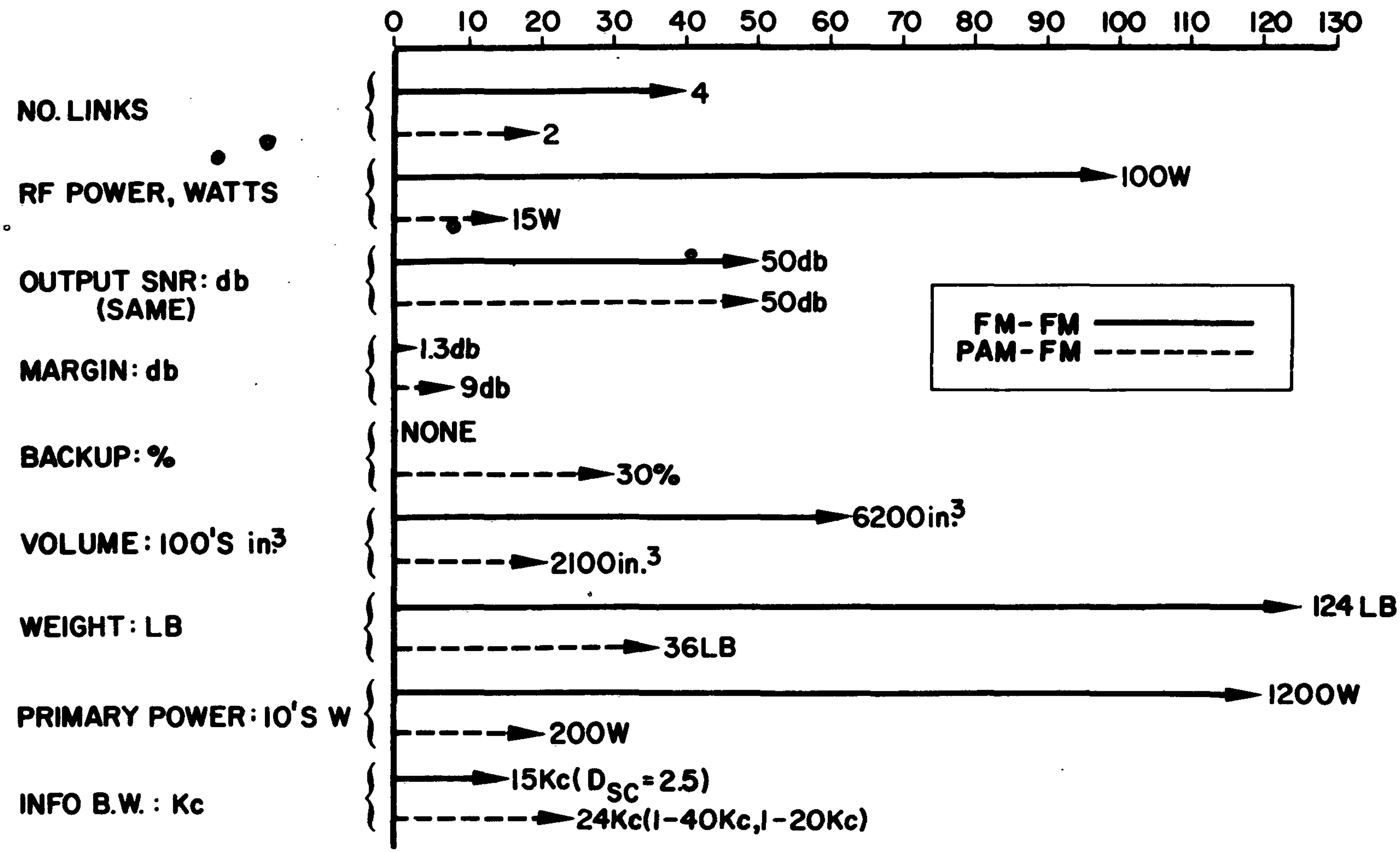


Fig. 3 Comparison of FM-FM and PAM-FM Equipment Needed to Satisfy Typical Flight Data Transmission Requirements

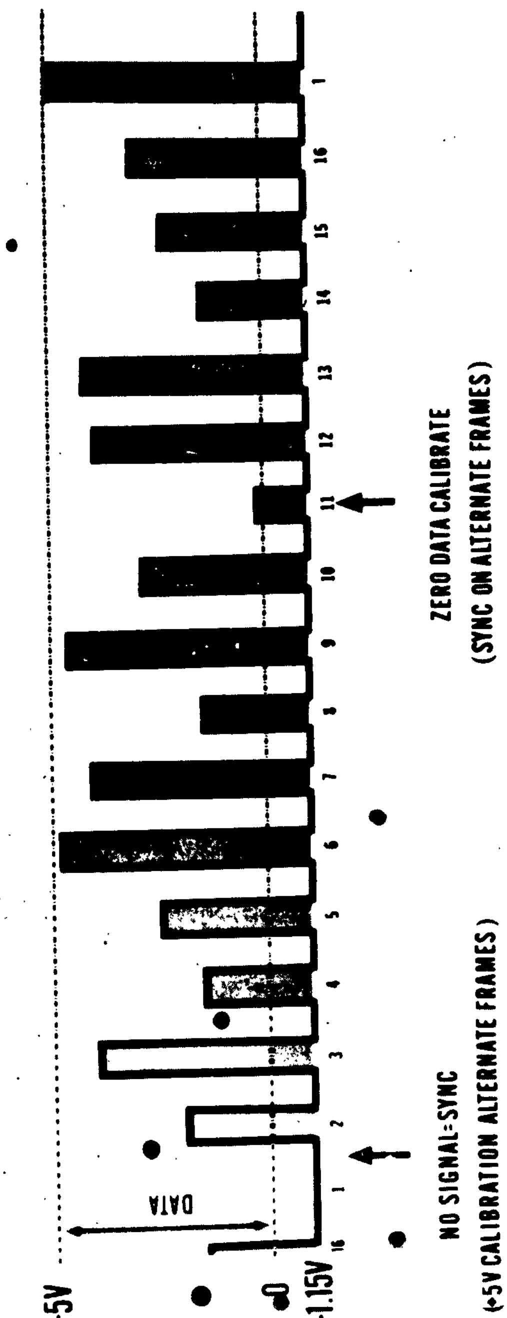


Fig. 4 PAM Signal Modulation Format

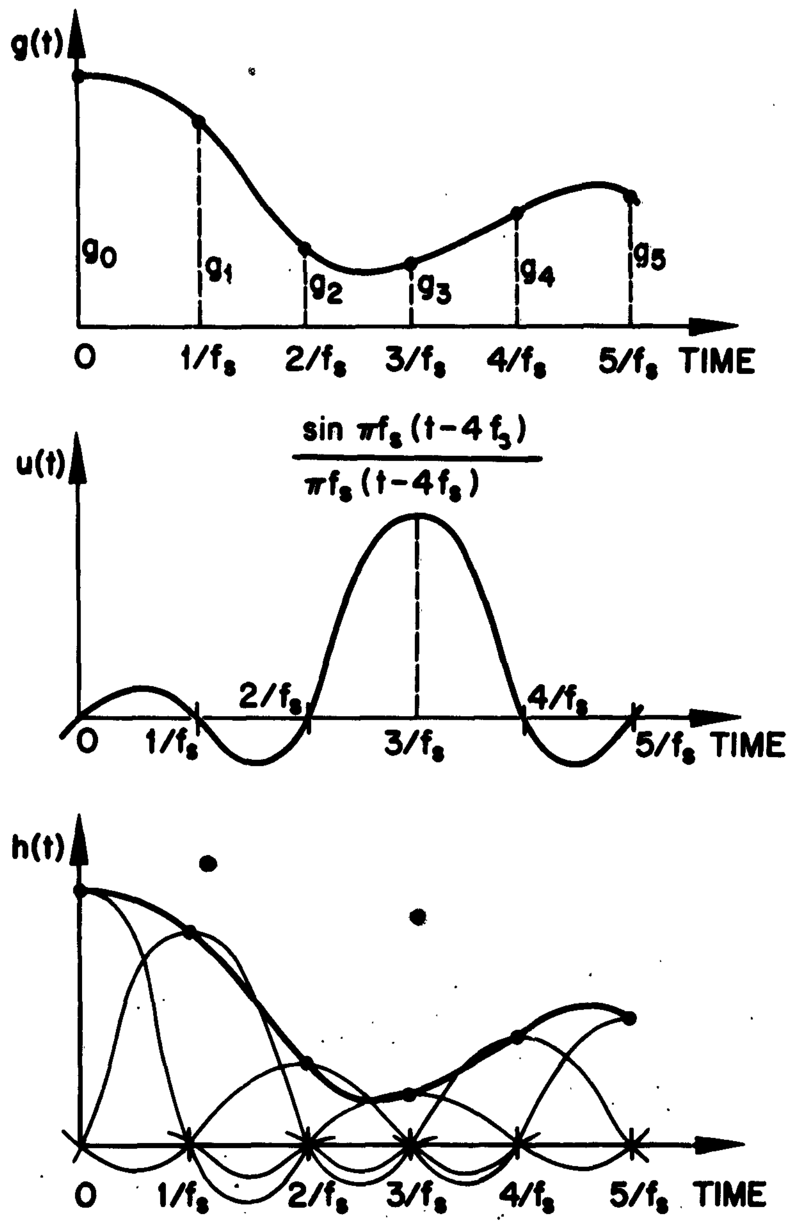


Fig. 5 Minimum Bandwidth Interpolation (Ref: H. L. Stiltz, Aerospace Telemetry, Prentice-Hall, 1961)

filters with sufficiently sharp cut-off. The low-pass filter removes all but the lowest component of the spectrum describing the sampled function, and this lowest component is the information frequency band itself. A low-pass filter with infinitely sharp cut-off will perform the interpolation perfectly. Practical filters with cut-off rates of 60 db/octave suffice if the sampling rate is raised from the theoretical $F = 2W$ to the rate of $2.5W$, a value generally adopted for the Lockheed PAM system. The total information bandwidth of the Lockheed system at, say, 40,000 cps is, then, 40,000/2.5 or 16,000 cps, i.e., 4 times the capacity of a standardized FM-FM system.

Caution must be exercised on one point. If the original information is contaminated by higher frequency noise, or if higher frequencies, beyond the range of interest, are naturally present, the instantaneous samples will be modified by these extraneous voltages and the resulting errors cannot be removed once the samples have been taken. These are the so-called aliasing errors, which must be combated by introducing sharp cut-off filters between transducer and commutator. For $F = 2.5W$, 30 db/octave filters will reduce rms aliasing errors to less than 1 percent.

Another practical problem to be considered in pulse-amplitude modulation is the potential crosstalk between adjacent channels in the time-sampling sequence (Fig. 6). Limited video bandwidth results in pulse deformation and spill-over from pulse to pulse. This problem could be eliminated by using a large video bandwidth with correspondingly large penalties in noise performance, and it is one of the common misconceptions about PAM that such wide bandwidth is necessary to preserve the exact amplitude values. However, amplitudes of the rounded pulses obtained after processing rectangular pulses through limited bandwidth are exactly proportional to the original amplitudes, so that the video bandwidth actually need not exceed the pulse frequency, and crosstalk can still be eliminated. This is done by choosing the proper demultiplexer duty cycle, so that the positive and negative parts of the pulse tails of previous pulses cancel insofar as the integration $\int_{\Delta t} A\,dt$ is concerned, which is performed to measure Amplitude A. It is necessary that the oscillating of the pulse tail occur in synchronism with the subsequent pulses; this happens automatically when the video bandwidth is appropriately chosen in the respect to the sampling frequency.

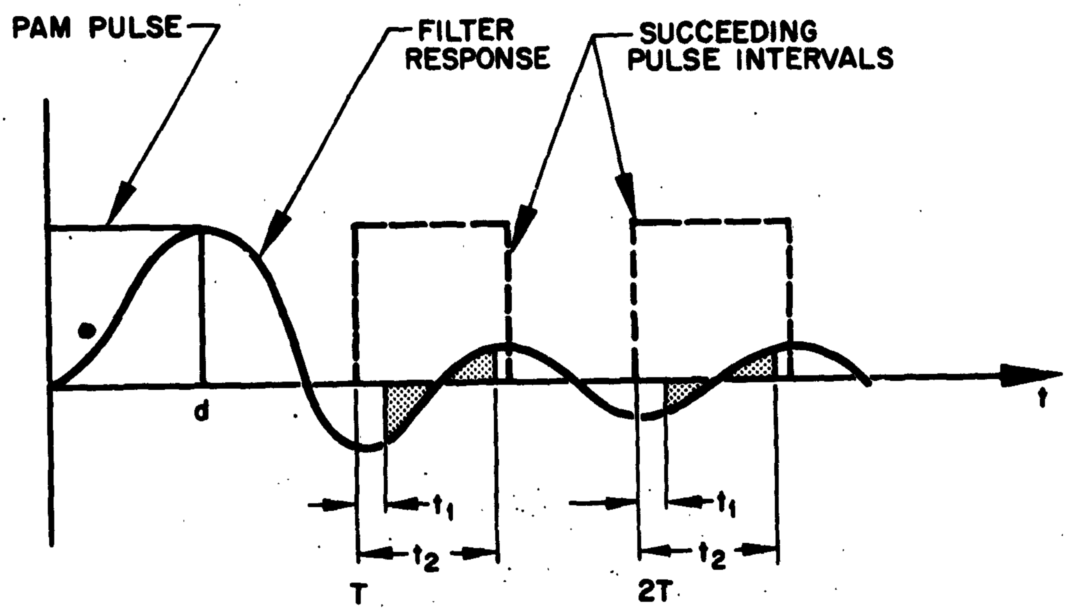


Fig. 6 Cross-Talk Areas (Ref: H. L. Stiltz, Aerospace Telemetry, Prentice Hall, 1961)

It will now be shown how the typical and diversified data requirement of Table 1 is handled by one PAM-FM system (Fig. 7). In the center of the block diagram we have the 16-channel main multiplexer. It is driven, as are the other multiplexers in the circuit, by the basic clock rate originating in the programmer. Channels 2 and 10, 4 and 12, 6 and 14, and 1 and 11 are paired so that the 4 vibration channels are sampled twice during each frame; this results in 5,000 samples/sec, corresponding to 2,000-cps data bandwidth as required. Such "supercommutation" allows, by simple circuit logic, the accommodation of high-frequency data exceeding the capabilities of the main, multiplexed channels.* Since all other channels require bandwidths less than the 1,000 cps of the main subchannels, further subcommutators are introduced which subdivide the sampling rate further, so that the channel rates correspond to the individual requirements. For example, data of Class 6 are sampled only every 128th frame, i.e., only one pulse out of 2,048 represents the amplitude of one individual channel of this kind. Millivolt data, such as originate from strain gages, are multiplexed at low level (a task difficult to accomplish until recently) and subsequently amplified to the customary 0 to 5-v level of high-level transducers. PAM-FM in this form is purely an analog system. Its accuracy is determined by signal-to-noise ratio and also by crosstalk and other limitations and lies between 1 and 2 percent of full scale, which is satisfactory for the bulk of the data. However, most measurement programs include a few data requiring higher accuracy, such as – in this case – the 28 payload measurements of 0.2 percent accuracy. Such data can be accommodated by using some of the pulses of the pulse train to represent digital data. Successive pulses of full or zero height could be used to transmit a binary word. Because of the ability of the system to reproduce amplitude to the order of 1 percent, however, it would be wasteful not to use intermediate amplitude steps for digital representation. In this system, we chose an octal code, i.e., eight discrete pulse-amplitude levels are possible, substituting for three binary digits. Three octal values thus correspond to a nine-digit binary code or 0.2 percent resolution. Because of the high signal-to-noise level of the system, the octal codes are received practically without error.

*Lockheed has built special vibration telemeters of 40,000 samples/sec total, containing only 8 channels with 2,000-cps frequency response each.

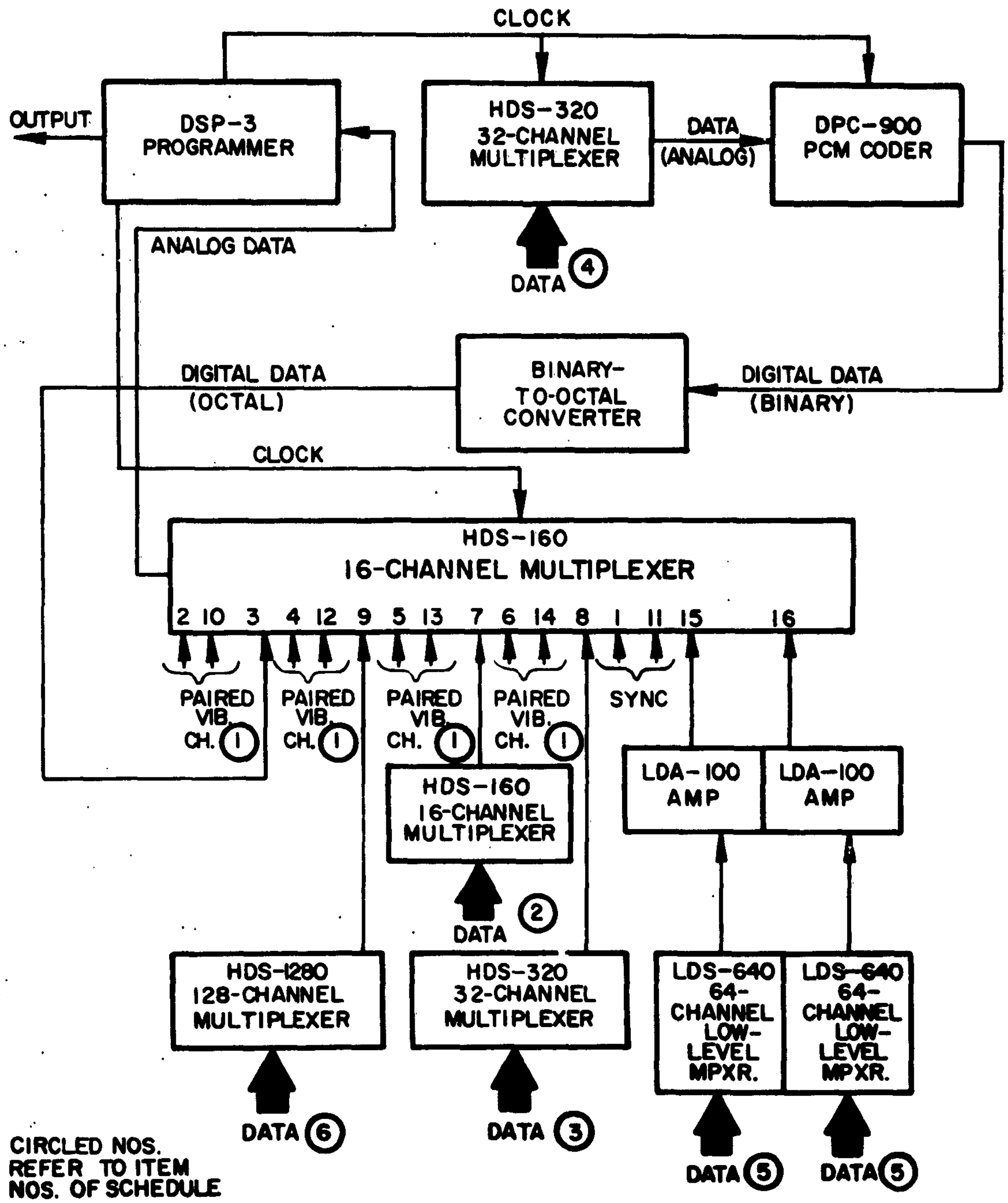
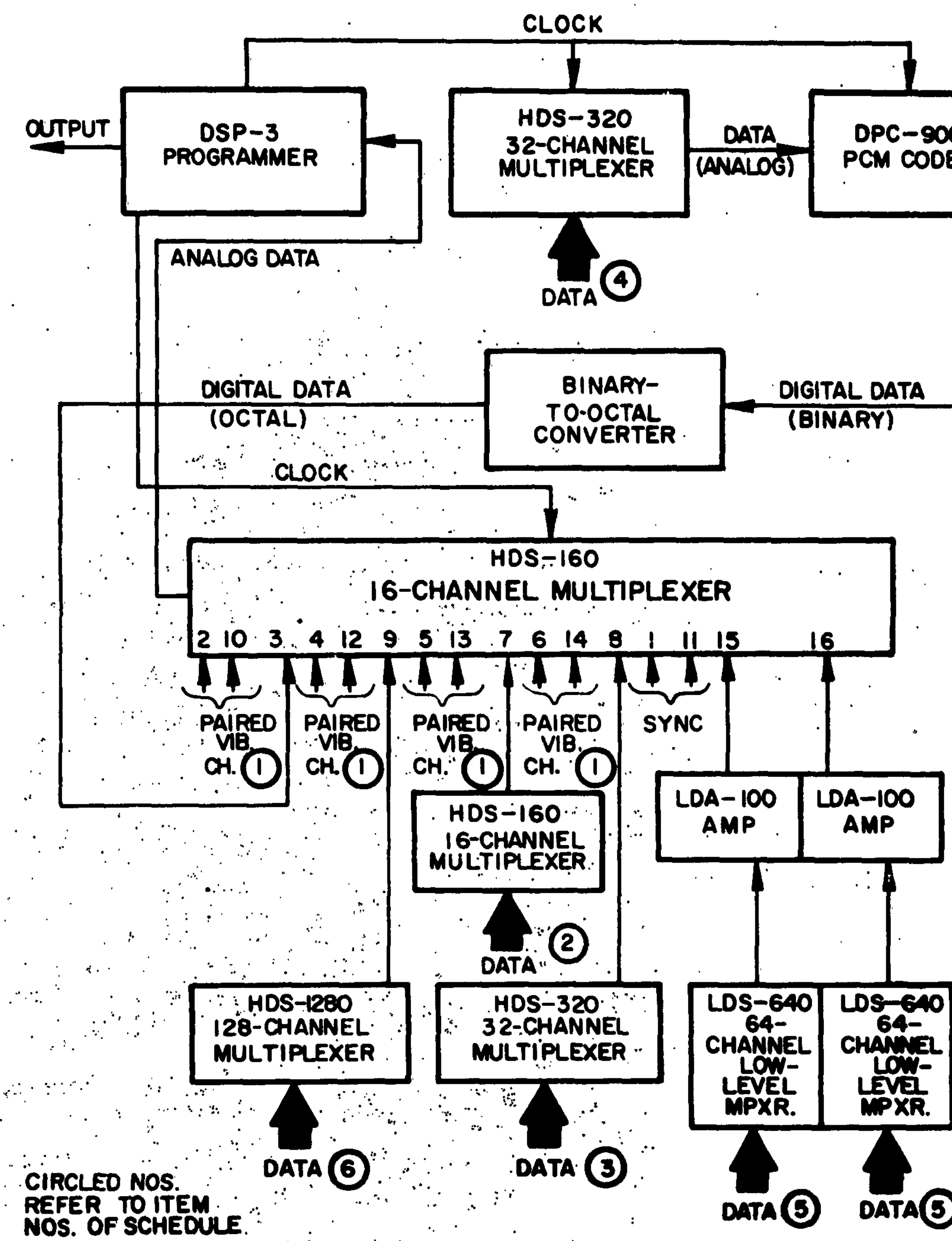


Fig. 7 Sampled Data System Typical Block Diagram

The channel statistics based on a flight instrumentation schedule of a satellite mission of a few years ago are shown in Table 3. A total of 535 measurements are involved, a moderate number by more recent standards. Figure 8 shows a graphical presentation of these data. Three vertical lines intersect the accumulated-total curves of percentage of total number of channels and percentage of total bandwidth. Line 1 shows that 50 percent of all data needs less than 1-cps bandwidth and jointly uses only 1 percent of full system bandwidth. Line 2 shows that 95 percent of all data requires less than 20-cps bandwidth and jointly uses only approximately 5 percent of total system bandwidth. Line 3 shows that the remaining 0.7 percent of all data channels consumes 50 percent of the total bandwidth. It is advantageous to select telemeter equipment that can be easily adapted to such a variety of diverse data-channel characteristics and their changes from test flight to test flight. PAM-FM is very well suited for the purpose. This flight instrumentation requirement was solved by using a combination of one PAM-FM link carrying most of the information and two FM-FM links. It would have been practically impossible to accommodate the data on four (or even more) FM-FM links. The chosen combination of systems was dictated at the time by such considerations as availability of ground stations in certain geographical areas for receiving payload data and increased reliability of data transmission during the boost phases by the use of two separate types of systems.

In the physical construction of a Lockheed PAM-FM telemeter, modular building blocks of subcommutation and of the other elements are used. This permits custom-tailored combinations to accommodate the channel requirements of any specific flight mission. Shown in Fig. 9 is a 64-channel low-level submultiplexer, revealing the 16 encapsulated modules. Volume is approximately 200 cubic inches and weight 6 lb. A patchboard arrangement enables the ground station to be completely adaptable to the space-borne configuration. Lockheed's operational PAM ground station, shown in Fig. 10, accepts the IF output of a communications receiver, determines proper synchronization intervals, processes the PAM pulse train, and yields both digital and selected analog outputs. The flexible nature of the system allows a predetection recorder, digital recorder, system test equipment, or extra processing modules to be added when required. In a



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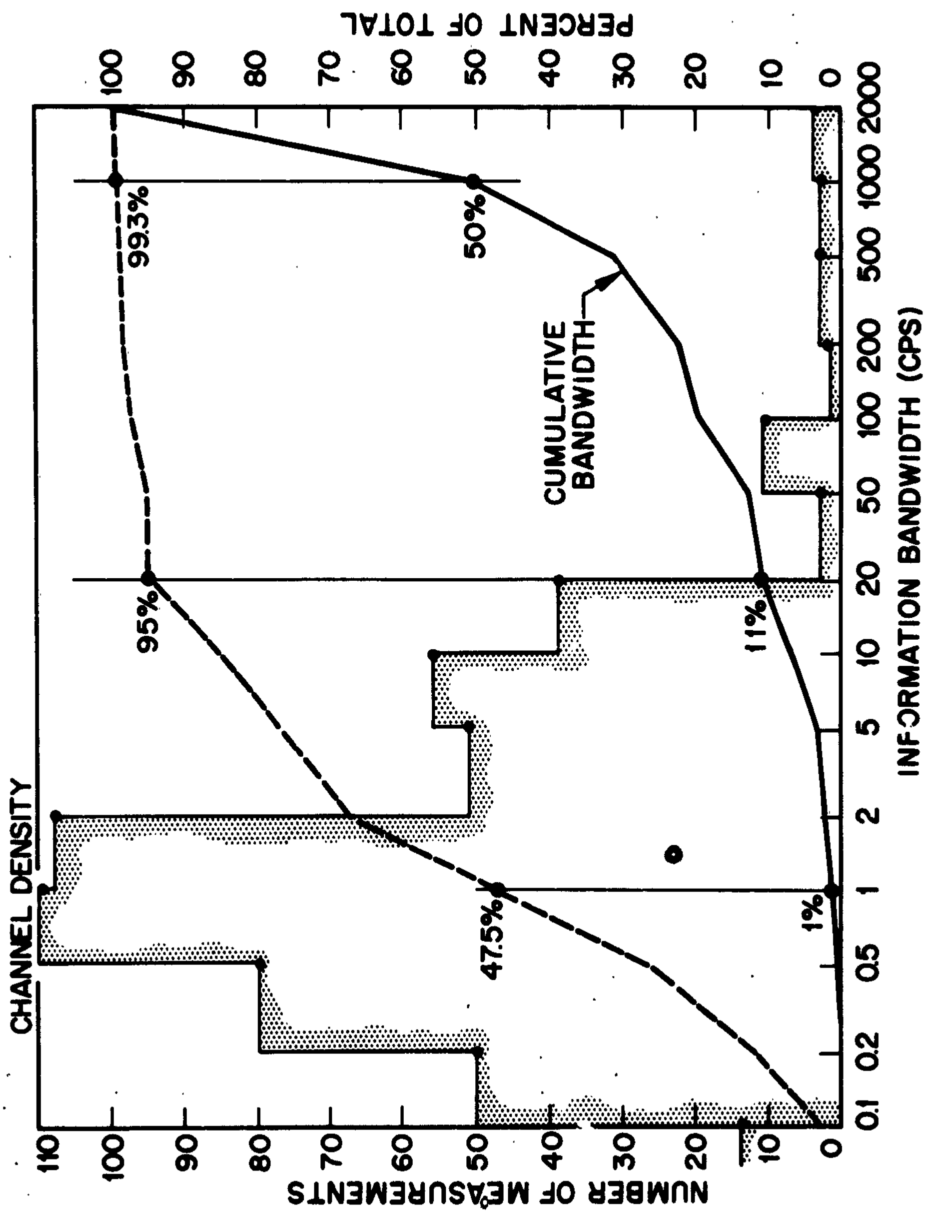

Fig. 8 Channel-Bandwidth Statistics For Satellite Mission

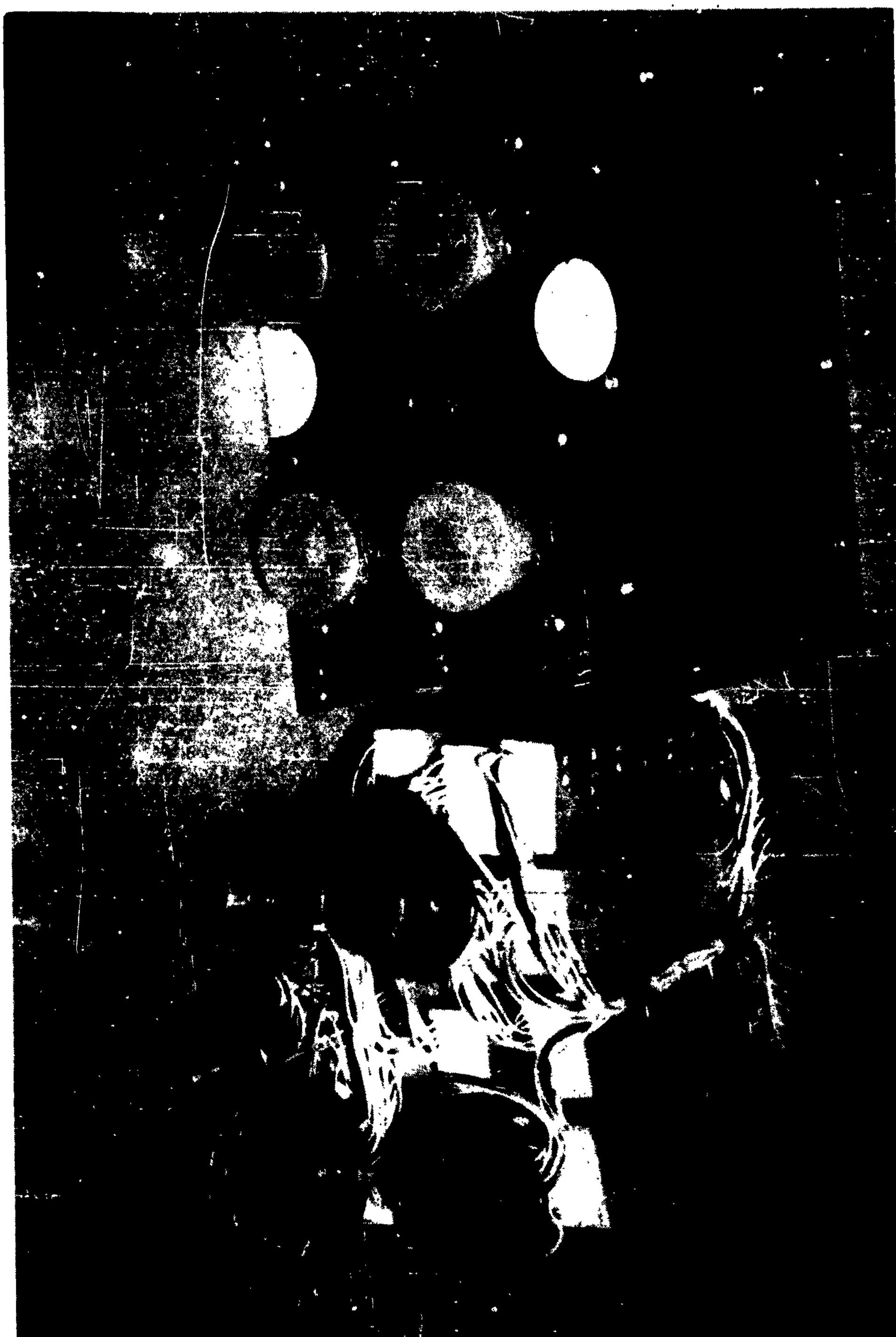

Fig. 9 PAM-FM Multiplexer Assembly

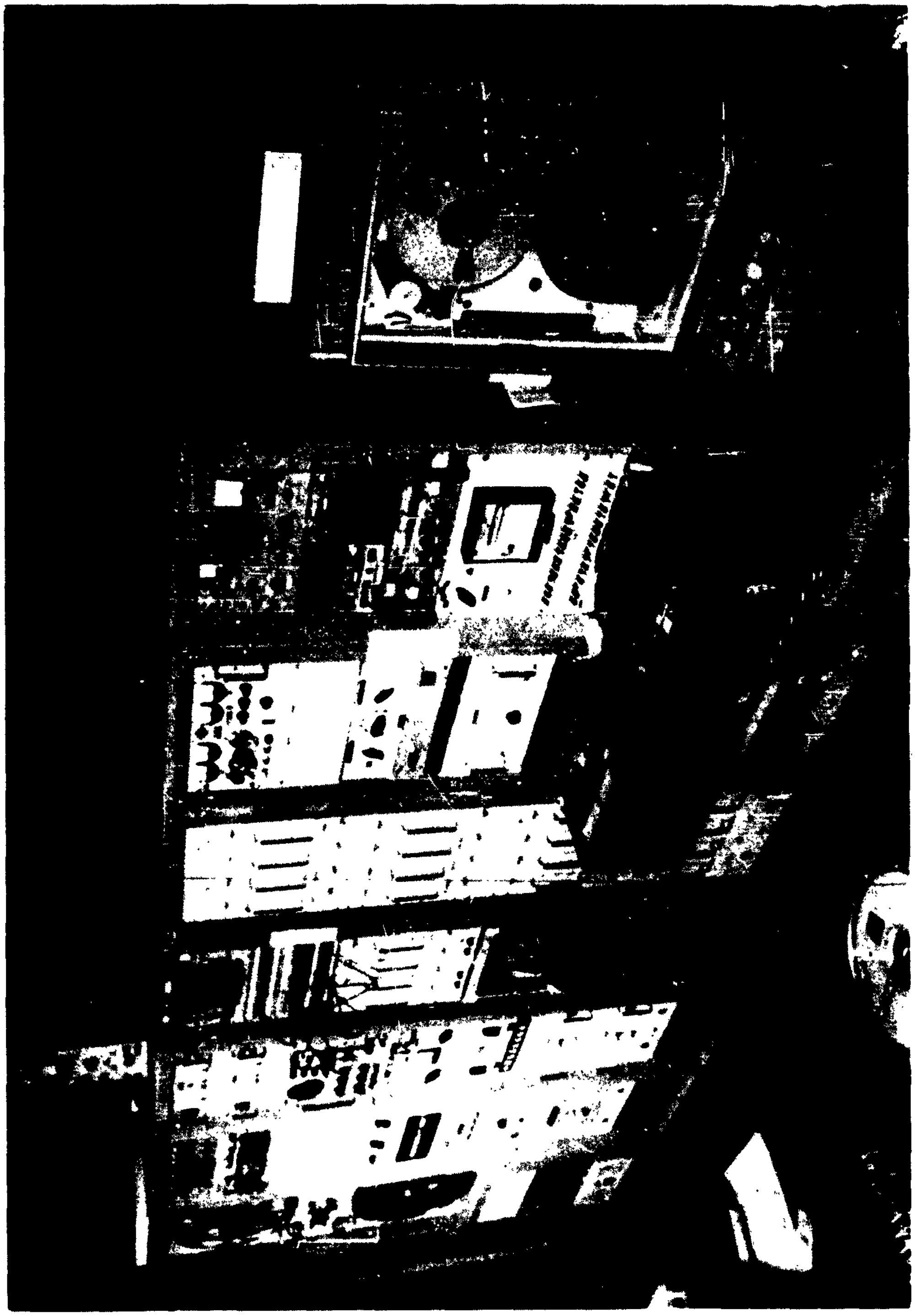

Fig. 10 PAM-FM Ground Station

typical installation such as shown, rack 1 contains the predetection wideband recorder rack 2 contains the r-f detection and subcarrier discriminators; racks 3, 4, 5, 6 contain sync separator, digitizer and output circuitry; and rack 7 consists of the digital tape recorder. It is important to note the patchboard for format selection. Figure 11 shows some recent LMSC space-telemetering transmitters, a VHF transmitter of 8-w output and weighing 1.3 lb, another one providing 15 w at VHF and weighing 2.3 lb, and the UHF type consisting of a UHF exciter and TWT amplifier, yielding 10-w power output.

5. PULSE CODE MODULATION SYSTEMS

There is a growing number of instances in which pure PCM systems merit consideration. Table 2 showed the comparison of various systems. Although the power per information bandwidth shown for PCM-FM slightly exceeded that for PAM-FM, the accuracy of the PCM system was somewhat better than that of the other systems despite the limited number of digits – namely five – chosen to match approximately the accuracy performance of the other systems. Two important reasons exist to favor PCM under certain circumstances. First, the reproduction of very-high-accuracy data is difficult with analog systems and much easier with digital systems. Table 4 illustrates this. The need for increased bandwidth and power occasioned by improving system accuracy to 0.5 percent is very moderate in the PCM-FM system since it is chiefly required only to extend the digital word by one bit; conversely the power penalty is considerable in the case of the analog PAM-FM system, and PCM-FM is now superior. It can be seen clearly from this chart and Table 2 that while analog systems have their place in moderate-to-low accuracy (> 1 percent) applications (such as represent most measurements using analog transducers), digital techniques are superior for high-accuracy (< 1 percent) requirements. Second, in complex space missions there is an increasing demand for programming, on-board editing and computing, and temporary storage of information. All of these are normally digital operations. Therefore, the transmission of data might logically follow this same digital pattern. It is anticipated that PAM-FM links and PAM/PCM-FM links as previously described might well carry the bulk of information during future missile tests and the booster phases of space missions.

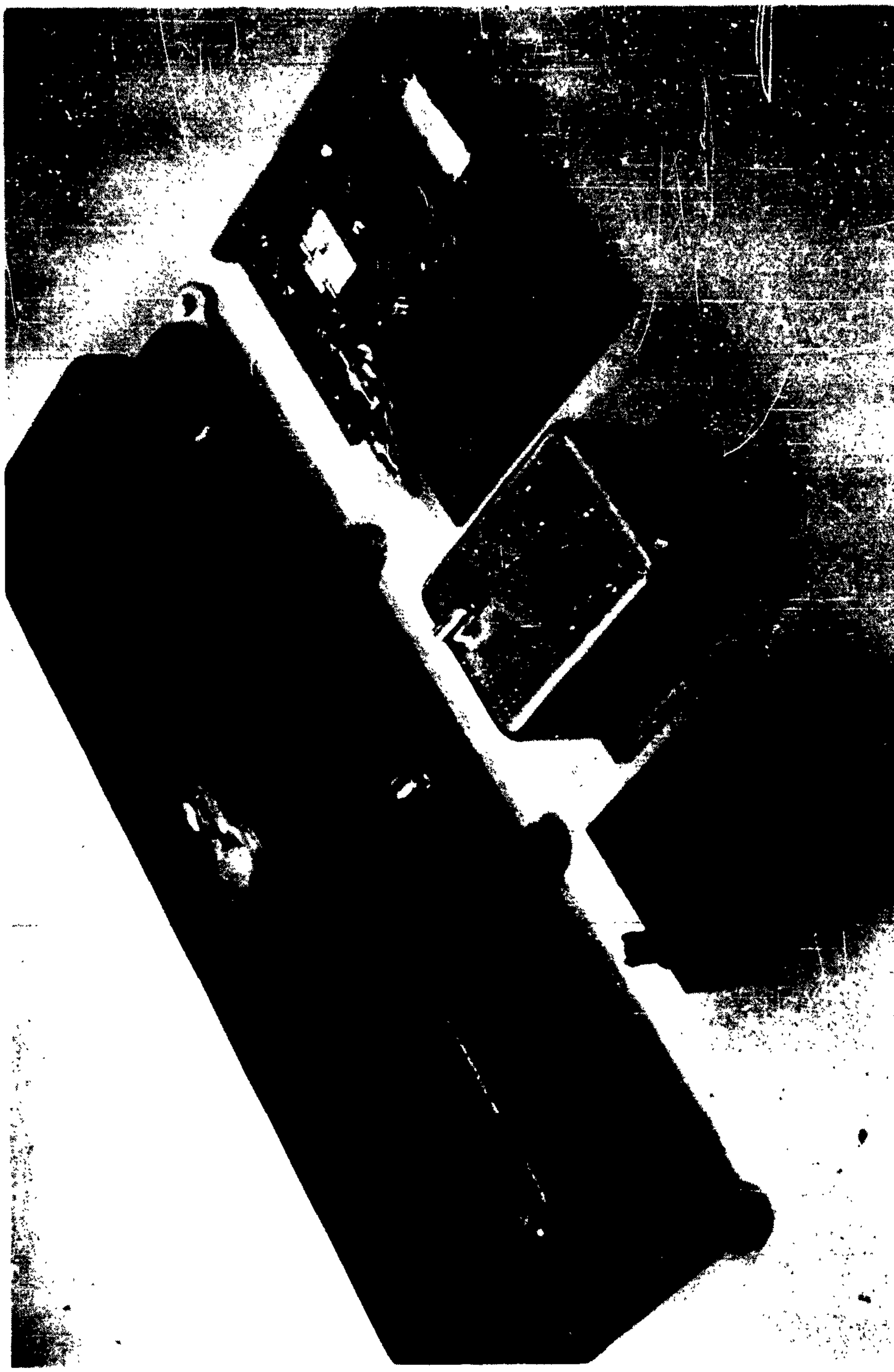

Fig. 11 Space Telemetering Transmitters

Table 4 PAM-FM AND PCM-FM COMPARISON AT 0.5% ACCURACY

	PAM-FM	PCM-FM
B_{INFO}	4 kc	4 kc
ϵ_{RMS}	0.5%	0.5% (1, 2)
$f_{sampling}$	10 kc	10 kc
f_{bit}	–	60 kc
DESIGN B_{IF}	80 kc	60 kc
PEAK DEV.	29 kc	30 kc
B_{VIDEO}	14 kc	30 kc
B_{PREMOD}	30 kc	30 kc
C/N (B_{IF})	13.2 db	13.7 db (2)
C/N (B_{INFO})	26.2 db (3)	25.5 db (3)
RF B.W. (-40 db)	80 kc	120 kc

(1) RMS QUANTIZING ERROR = $2^{-6}/\sqrt{12}$ = 0.45%

(2) BIT ERROR PROBABILITY = $10^{-5} \rightarrow$ 0.22% EQUIVALENT RMS ERROR

(3) PCM-FM IS NOW BETTER THAN PAM-FM, AND WILL BECOME MORE CLEARLY SO FOR $\epsilon_{RMS} < 0.5\%$

Telemetering connected with space flight in the most advanced sense, including missions to the moon and the planets, is expected to be completely digital in nature, particularly since the somewhat wider bandwidth required is compatible with the very high carrier frequencies likely to be used for such undertakings.

It is fortunate that most of the effort spent on the development of PAM-FM components is directly applicable to a PCM-FM embodiment. Equipment presently under development at Lockheed for the NASA GEMINI program is based on an 8-digit binary PCM format. Some of the datum values to be transmitted are digital from the outset, while analog measurements are converted to digital code form prior to being interleaved into the multiplex pulse train. In this case, not only is there a requirement for a limited amount of high-accuracy data, but also for integration with an 8-bit airborne digital programmer and storage facility. The choice of pure PCM-FM was a logical step. Although conversion equipment is needed for digitizing analog transduced outputs, this disadvantage is essentially compensated by the advantages gained through using a single data format.

In the generic class of PCM systems, there are other types which use expanded digital codes for the purpose of gaining superior performance. As an example, it might be worth mentioning the DIGILOCK system, developed by Space Electronics Laboratory, Inc., for the Jet Propulsion Laboratory of NASA and the Air Force Special Weapons Center for certain long-range space-probing missions. In this system, to give an example which has been implemented, 5-bit digital words, corresponding to 32 discrete levels of a sampled measurand, are represented for transmission purposes by 32 mutually orthogonal 16-bit binary codes of the Reed-Muller type and sent by phase modulation of the RF carrier (Table 5). The use of 32-level quantization permits about 1 percent rms accuracy to be attained under good signal-to-noise conditions, and the corresponding resolution is about 3 percent of full scale. The restricted property of mutual orthogonality among the 32 16-bit binary codes is achievable by selection of codes from the much larger set of 2^{16} possible combinations of ones and zeros. This orthogonality permits correct recognition of the transmitted code sequence under quite

Table 5 REED-MULLER CODES (16 BITS, 32 ORTHOGONAL CODES)

UNITS																
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
4	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1
8	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
16	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1

Example (Add without carryover)

CODE NO. 23																
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
4	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1
16	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
23	1	0	1	0	0	1	0	1	0	1	0	1	1	0	1	0

marginal noise conditions (when several code digits may be in error), by using a corresponding set of matched filters in the receiver. It is for this reason, wider noise bandwidth notwithstanding, that orthogonally-coded systems surpass uncoded binary PCM systems in effectiveness of power utilization – in the case of DIGILOCK by about 3db.* This superiority is not, however, equivalent to increased information-theoretic efficiency in the sense of Shannon's basic channel capacity formula: $C = W \log (1 + S/N)$, because the wider bandwidth occupied by the coded system could be even more advantageously exploited by the use of yet more complex code structures, e.g., error-correcting codes. Still, DIGILOCK is closer to the theoretical Shannon limit than any of the other telemetry systems in current use. Although 3 db is not a spectacular improvement, it does mean 40 percent increased transmission range which, in the interplanetary context, may be equivalent to maintaining communications through many additional months of space travel.

As one of the time-division systems, DIGILOCK can be adapted to changing requirements even if these occur during flight. Should, during a deep-space mission, for example, the bandwidth become too large for the available space vehicle transmitter power, the data rate could be reduced to, say, one half. On the ground, every other tap only of a delay-line matched filter could then be used, corresponding to the longer times between pulses.

6. METHODS OF COPING WITH THE FLOOD OF DATA

The increasing complexity of missile and space missions puts an ever-increasing demand on telemetering systems to transmit a great amount of data simultaneously. For huge, multi-stage rockets, such as are presently emerging from the factories or are in the planning stage, it may be necessary to provide as many as 10, 15, 20 or more simultaneous high-speed RF links. Figure 13 shows that some of the most advanced missions require in excess of 1,000,000 data points/sec, corresponding, for example, to something like 25 simultaneous PAM-FM systems with a sampling rate of 40,000/sec each.

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*See Fig. 12.

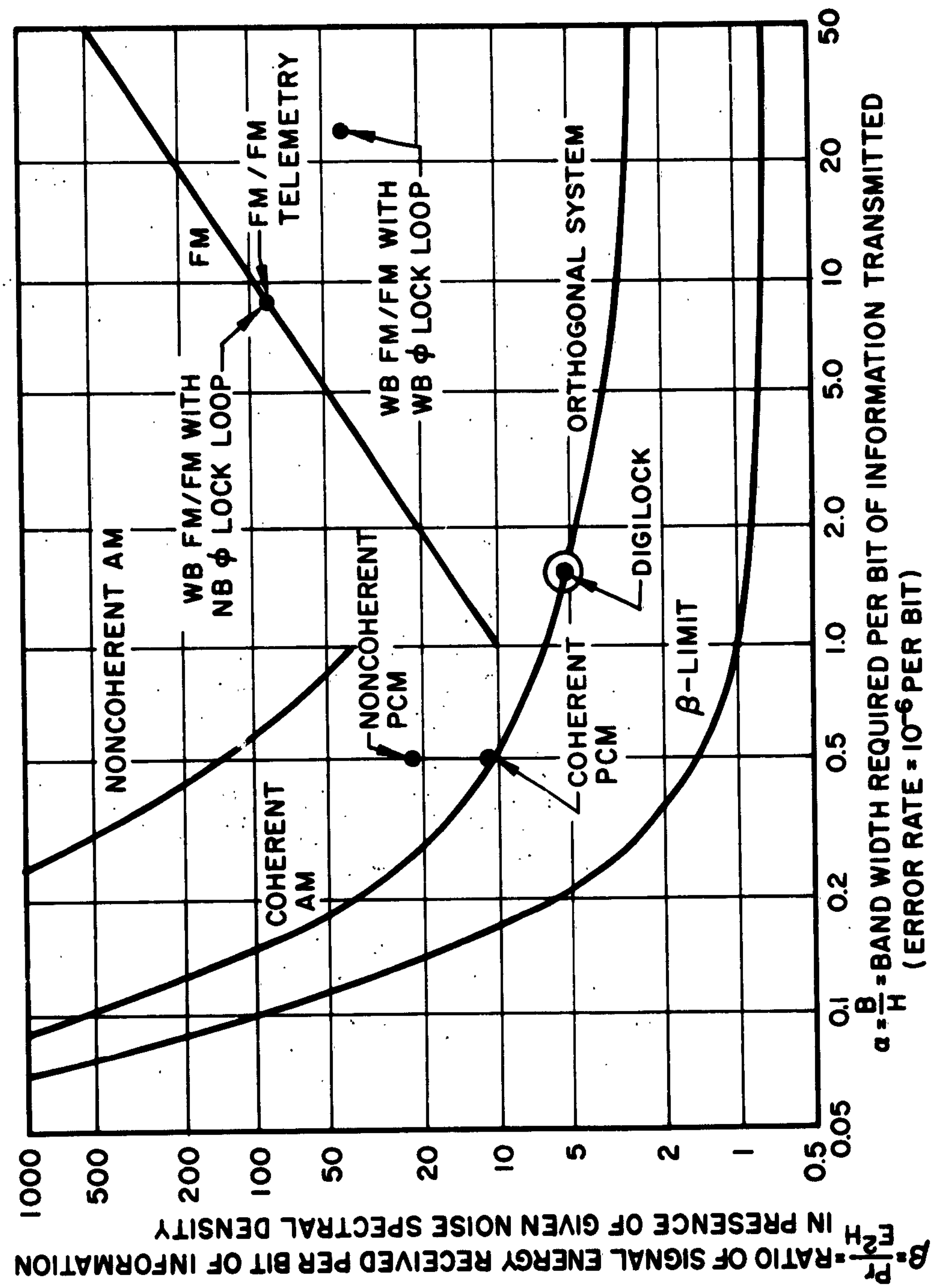

Fig. 12 Comparison of the Communication Efficiency of Various Systems (From Missile & Rockets; July 13, 1956 – Modified)

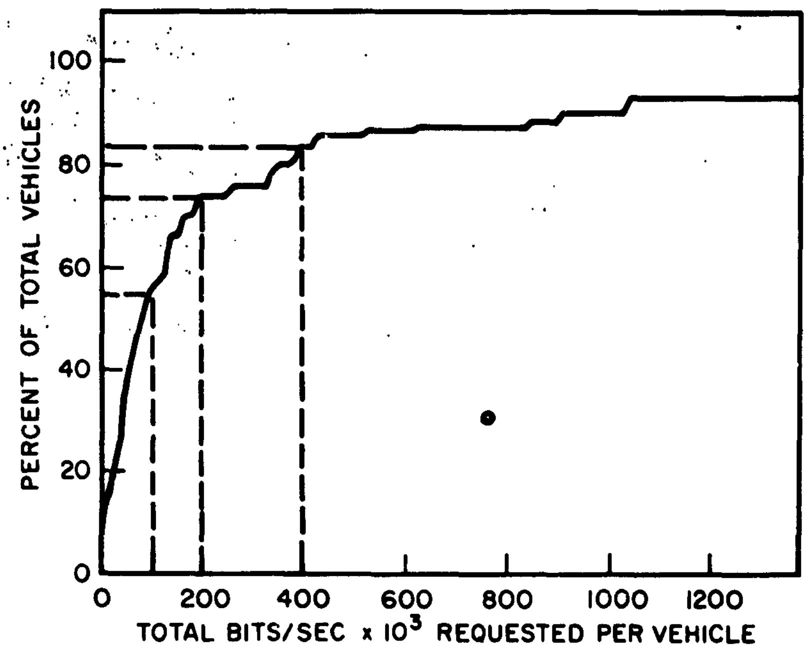

Fig. 13 Cumulative Distribution of Information Requirements for all Vehicles (total number of vehicles 100). From Aviation Week, April 4, 1960

The problem can be attacked in two ways. First, continued attempts are made to produce more efficient telemetry systems of low power, weight, size, and bandwidth characteristics. PAM-FM by Lockheed is a typical example. Although the requirement for flexibility points in the direction of time-multiplexed systems, it is worth noting that serious attempts are presently being made by the advocates of continuous-data systems to increase the efficiency of such systems through the application of relatively advanced techniques, notably single sideband. Two systems stand out: an SSSC-FM system conceived and developed by the Telemetry Group at Marshall Space Flight Center and an FM-SSSC system favored by Dr. Rauch of the University of Michigan. Table 6 shows how these two systems compare with the ones previously discussed. The Marshall Space Flight Center system, built by Dynatronics, Inc., has 15 sub-channels, each with a 0.03 to 3.0-kcps frequency response. Total information bandwidth is thus approximately 45 kc, more than ten times the capacity of the standard FM-FM system. We note that the RF power required is greater by approximately +10 db compared to the PAM system of 4-kc bandwidth stipulated in Table 2. Since, however, the SSSC-FM system carries 10 times the information volume, this modulation technique is as efficient as PAM-FM – as should be the case, since both are orthogonal-subcarrier, i.e., frequency-and time-difision, respectively, multiplex FM systems).

The price paid for this improvement over FM-FM in continuous-data system capacity is complexity of synchronization and demodulation. Furthermore, the application of rectangular pulses to a single-sideband system results in considerable envelope overshoot. This could be quite disadvantageous if subcommutation – such as practical in the FM-FM system – is applied to more than a very few subcarrier channels; SSSC-FM is essentially a peak-limited system at the subcarrier level. The use of rounded pulses would reduce the problem and may be considered in conjunction with the transmission of digital codes via some of the subcarriers. This leads to a partial PCM/SSSC-FM format and to increased system flexibility somewhat at the expense of total system capacity. If use can be made of the full information capacity of the SSSC-FM equipment, "only" about 12 SSSC-FM links would be required to handle the projected million-data-point/sec requirement of future missions.

Table 6 COMPARISON OF SSSC-FM AND FM-SSSC (POWER REFERENCE 0 db For PAM-FM, Table 2)

	SSSC-FM (NASA-MARSHALL)	FM-SSSC (OPTIMIZED USING REDUCED-INDEX ± 7.5% IRIG SUBCARRIERS (5)) (L. L. RAUCH)
B_{INFO}	45 kc (1, 3)	7.4 kc (5)
RMS ERROR	2% of f.s.	2% of f.s.
DESIGN B_{IF}	300 kc	80 kc
PEAK DEV.	125 kc (40 kc RMS)	–
B_{VIDEO}	75 kc	80 kc
B_{PREMOD}	75 kc	80 kc
C/N (B_{IF})	13 db (2)	7.2 db (6)
C/N (4 kc)	31.75 db	20.2 db
RELATIVE REQ'D POWER	10.1 (3) +10.05 db	0.707 (7) -1.5 db
SPECTRUM BW	~ 300 kc (4)	80 kc

(1) AS PROPOSED BY NASA-MARSHALL: 15 × 3 kc

(2) GOVERNED BY THRESHOLD FOR LOWEST BASEBAND CHANNEL

(3) POWER AND B_{INFO} IN ABOUT SAME PROPORTION RELATIVE TO PAM-FM

(4) ESTIMATED BY ANALOGY WITH FM-FM

(5) FM SUBCARRIER MODULATION INDEX REDUCED TO D = 2.72 AT ±7.5% DEV.

(6) SUBCARRIER THRESHOLD FOR D = 2.72

(7) TOTAL SIDEBAND POWER

It appears that the reverse procedure, namely, FM subcarriers in combination with single-sideband suppressed-carrier RF transmission, is – theoretically – the most attractive of all systems compared so far, slightly surpassing even PAM-FM in relative required power. However, FM-SSSC does not have quite the flexibility of the latter, although subcarrier commutation can be applied without complications.

The other and much more profound way of approaching the multi-link problem consists of attacking the evil at its source.

7. REDUCTION OF INFORMATION BANDWIDTH

Data as presently transmitted in our many missile and space missions are, to a considerable extent, redundant. Samples may be taken too frequently because the rate is determined by the highest frequency likely to be encountered and, secondly, because it is often impractical to sample at very low rates (say, one per second or even minute) because of the additional circuitry involved. Although the engineering of multiple links to carry all the information provided by vehicles relatively close to earth is in the realm of practicality, the digestion of the astronomical amounts of data gathered, e.g., during extended satellite missions, is an appalling task. (Even now, 65 million dollars are spent annually in the U. S. on magnetic tape for recording telemetered data.) Further, limitations imposed by the availability of primary power and physical constraints on equipment bulk clearly show that ways must be found to reduce the amount of information transmitted by deep-space missions. The power limitations are well demonstrated by Table 7.

Effective information bandwidth reduction can be achieved by:

- Limiting the upper information frequency to be transmitted to the bare minimum and reducing the number of samples accordingly
- Reducing the accuracy of transmission to the bare minimum
- Reducing sampling rate below value specified by sampling theory and making use of a-priori information on data characteristics on the ground to obtain intermediate data by interpolation

Table 7 ILLUSTRATIVE LINK CALCULATIONS

LINK PARAMETER	EARTH SATELLITE	MOON	MARS	EDGE OF SOLAR SYSTEM
RANGE, nm	4,500	$0.25 \cdot 10^6$	$200 \cdot 10^6$	$3200 \cdot 10^6$
PROPAGATION LOSS, db	-178	-213	-271	-295
REQUIRED TRANSMITTER POWER, WATT	0.16	500	$3 \cdot 10^8$	$8 \cdot 10^{10}$

FOR ALL LINKS: FREQUENCY 2300 Mc
TRANSMITTER ANTENNA GAIN 12 db
RECEIVER ANTENNA GAIN 50 db
MISC. FEED LOSSES 6 db
RECEIVER NOISE (B_{IF} = 600 kc, NF = 4 db): -142 dbw

- Reducing the numbers of samples transmitted in accordance with an on-board computer which extrapolates data by using channel characteristics known a priori and by transmitting deviations from the expected values only

At Lockheed a hybrid-type system has been developed in which some of the characteristics of the above approaches are combined in a very straight-forward scheme which is simple to implement. The system is based on the premise that a measured quantity is of little interest as long as it does not change appreciably. Therefore, circuitry is proposed which initiates transmission only when the measurement value changes significantly from the previous sample. Whenever a value is transmitted, this is done with the full system accuracy. Reference is made to Fig. 14. Suppose a measurement value is transmitted at time t_o . After an interval commensurate with the highest frequency component, i.e., slope, of the data, the transducer is again interrogated. It is now determined whether the new value lies within or without certain incremental boundaries stored in the data compressor at time t_o . These limits are determined by pre-selection for the particular channel and applied whenever a measurand is investigated for its behavior. The tolerance bands on the upside and on the downside can be chosen independently. They can be of the order of 1 percent (with little attendant data reduction) or, say, 20 percent of full scale (resulting in considerable compression). If the new measurement value is within the boundaries applied, it is not retained for transmission, and the boundaries are returned to the memory of the compressor to be reapplied at the next sampling time. If the measurement value exceeds the boundaries, it is forwarded for processing and transmission. Concurrently, the tolerance bands are shifted so as to bracket this new value, and the resulting revised boundaries are stored for application at the next sampling time. The procedure described is applied to all channels of the high-capacity system. When the amplitude variations of a channel are small and/or slow, the number of samples chosen for transmission can be vastly smaller than the number of primary interrogations, so that a considerable saving occurs through reduction of redundancy. The saving depends on the frequency distribution or spectrum of the data: The stronger the high-frequency elements relative to the low frequency level, the less is the reduction in number of samples necessary. This is

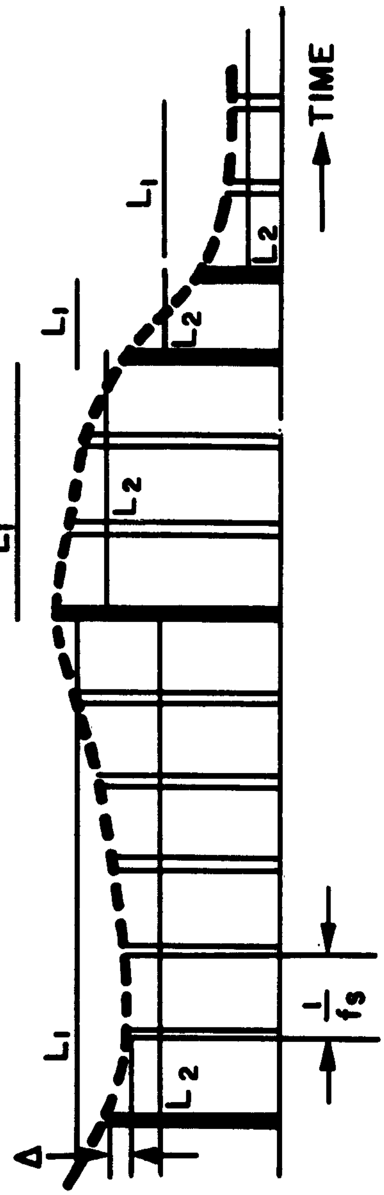

Fig. 14 Sampled Data Waveform

shown in Fig. 15 for theoretical cases which presuppose noise-like data with the postulated power spectral density distributions. A great amount of data actually received during prolonged satellite flights and thought to be typical was also analyzed with the aid of a computer routine which simulated the operation of the data compressor. Appropriate data compression factors were thus determined for a number of realistic cases, and were found to range up to the order of 30.

Since the data samples selected for transmission from most channels occur at irregular intervals, it is necessary to identify them both as to channel origin and the time period elapsed since the last sample transmission. This is achieved by means of a code word added to the code representing the measurement value. It is further necessary before transmission to order the data samples into a sequential relationship, with uniform time intervals between samples. This is accomplished in a special buffer storage. A queueing problem exists at the input of the buffer, comparable to the queueing of many individual subscribers using the trunk lines of a telephone network. Investigations show, however, that only moderate storage capacity is required in the buffer to reduce the overflow probability to negligible proportions. This, naturally, presupposes normal behavior of the channels involved. A catastrophic vehicle failure might however bring about a burst of data from all affected channels. It will be necessary to accord this case special consideration.

After demodulation and channel separation on the ground, rather accurate data points occurring at irregular intervals are obtained. They can be plotted by using knowledge of the duration of the interval between the irregular samples for the advancement of the recording tape or paper; they can also be handled in a computer for the purpose of reducing the uncertainties of the measurement values between the samples by the application of Lagrange interpolation functions. The latter procedure can be expected to produce probable intermediate values of accuracies higher than given by the boundary brackets applied.

The system under development at Lockheed provides an effective immediate solution to a problem that has been woefully apparent for quite some time. Part of the reason that

(1) $F(\omega) = k_1 \exp(-5 f^2/fm)$; for $|f| \leq fm$
$= 0$ otherwise

(2) $F(\omega) = k_2$; for $|f| \leq 0.1\ fm$
$= 0.01\ k_2$; for $0.1\ f_m < |f| \leq fm$
$= 0$ otherwise

(3) $F(\omega) = k_3 \exp(-25 f^2/fm^2)$; for $|f| \leq fm$
$= 0$ otherwise

(4) $F(\omega) = k_4 \exp(-5 f/fm)$; for $|f| \leq fm$
$= 0$ otherwise

(5) $F(\omega) = k_5 (1 - f/fm)$; for $f \leq fm$
$= 0$ otherwise

(6) $F(\omega) = k_6$; for $|f| \leq fm$
$= 0$ otherwise

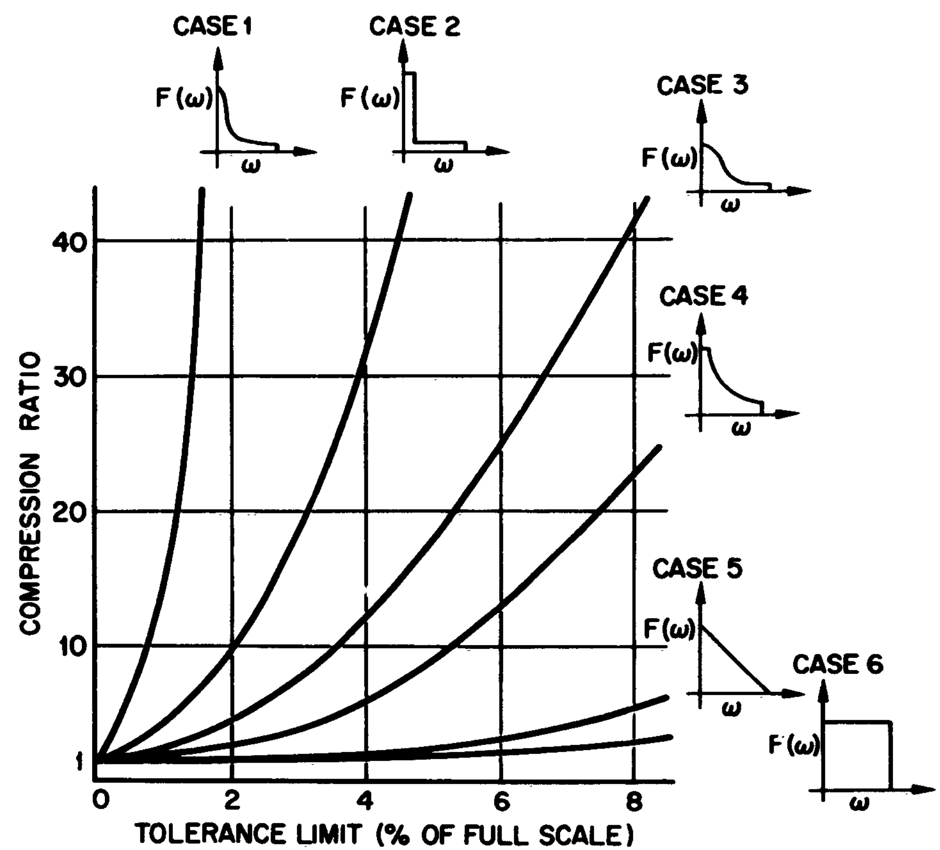

Fig. 15 Compression Ratio For Several Spectral Densities

on-board data processing schemes have not, heretofore, found widespread application can be found in the availability of equipment allowing the luxury of transmitting everything, and part in the apprehension of the somewhat complex compressor circuitry (with its possible reduction of reliability and additional cost) and partly in user distrust of the machine's judgment in editing his data. It is necessary indeed to weigh these various factors in each specific case.

Present investigations, fortunately, indicate that modern, solid-state space computer technology is advanced to the point where the addition of a data compressor is worth considering. Particularly in cases involving high data rates and where transmitted power is at a premium, it might well become a virtual necessity to do so. It must be noted, however, that the scheme does not lend itself well to applications having information sources resembling white noise, such as vibration transducers. If any sizable reduction of information bandwidth is to be obtained here, alternate additional techniques must be considered. By the addition of a bank of filters, for example, power spectral density measurements can be obtained, whose transmission requires much less than the waveform bandwidth and which can be even further reduced by a data compression scheme such as outlined above, for which they are well suited.

Special compression circuitry, adapted to data exhibiting behavior known a priori, will merit increased attention when the ultimate in bandwidth economy is needed for deep-space missions. As an example, the transmission of electrocardiac voltages from an astronaut in space belongs to this category. So long as the waveform follows a normal, pre-recorded pattern, with certain allowances for variation in pulse rate and blood pressure, no more than the occasional transmission of an "O.K." might be necessary to actuate a green pilot light in the blockhouse. Even if drastic changes worth medical analysis occur, the transmission of rate, amplitudes, certain phase relations, overshoot conditions, and quotients of voltage-time areas could be accomplished within a much smaller bandwidth than would be required to transmit the actual complex waveform. In this and similar cases, specialized computers could generate code words to characterize the essential behavior of the measureand. These again would need to be transmitted only in case of a change defined by pre-set tolerances.

A discussion is presented of telemetry systems and requirements for [illegible]'s and space applications. Various mo[illegible]tion methods and concepts are presented.

~~5-10-02-20~~

8. SUMMARY

The development of concepts and equipment for telemetering systems of high data capacity and efficiency has progressed considerably during recent years. For the majority of data connected with large-scale rocket and space missions, the PAM/PCM-FM system is well suited because of its adaptability, economy of bandwidth and power, and ability to handle some high-accuracy data. If the bulk of the data to be transmitted demands high accuracy and/or the data format must be compatible with computing equipment aboard the space vehicle, PCM-FM is most appropriate. In any case it becomes progressively more important to combat the flood of data descending on us from outer space. Th~~is can~~ best be achieved by information bandwidth compression schemes based on elimination of redundancy. Techniques such as are presently under development ~~at Lockheed~~ lead to compression factors of the order of 30, referenced to the indiscriminate data-transmission practices of today.

Acknowledgment

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A discussion is presented of telemetry systems and requirements for missile and space applications. Various modulation methods and concepts are presented. ~~5-10-62-20~~

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